DIRECT AND LARGE-EDDY SIMULATION VI

ERCOFTAC SERIES

VOLUME 10

Series Editors

R.V.A. Oliemans, *Chairman ERCOFTAC,*
Delft University of Technology, Delft, The Netherlands

W. Rodi, *Deputy Chairman ERCOFTAC,*
Universität Karlsruhe, Karlsruhe, Germany

Aims and Scope of the Series

ERCOFTAC (European Research Community on Flow, Turbulence and Combustion) was founded as an international association with scientific objectives in 1988. ERCOFTAC strongly promotes joint efforts of European research institutes and industries that are active in the field of flow, turbulence and combustion, in order to enhance the exchange of technical and scientific information on fundamental and applied research and design. Each year, ERCOFTAC organizes several meetings in the form of workshops, conferences and summerschools, where ERCOFTAC members and other researchers meet and exchange information.

The ERCOFTAC Series will publish the proceedings of ERCOFTAC meetings, which cover all aspects of fluid mechanics. The series will comprise proceedings of conferences and workshops, and of textbooks presenting the material taught at summerschools.

The series covers the entire domain of fluid mechanics, which includes physical modelling, computational fluid dynamics including grid generation and turbulence modelling, measuring-techniques, flow visualization as applied to industrial flows, aerodynamics, combustion, geophysical and environmental flows, hydraulics, multi-phase flows, non-Newtonian flows, astrophysical flows, laminar, turbulent and transitional flows.

The titles published in this series are listed at the end of this volume.

Direct and Large-Eddy Simulation VI

Proceedings of the Sixth International ERCOFTAC Workshop on Direct and Large-Eddy Simulation, held at the University of Poitiers, September 12–14, 2005

Edited by

ERIC LAMBALLAIS

University of Poitiers, Laboratoire d'Études Aérodynamiques, Futuroscope Chasseneuil Cedex, France

RAINER FRIEDRICH

Technische Universität München, München, Germany

BERNARD J. GEURTS

University of Twente, Enschede, The Netherlands

and

OLIVIER MÉTAIS

ENSHMG/INPG, St Martin d'Hères, France

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4909-9 (HB)
ISBN-13 978-1-4020-4909-5 (HB)
ISBN-10 1-4020-5152-2 (HB)
ISBN-13 978-1-4020-5152-2 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Printed on acid-free paper

To Frans T.M. Nieuwstadt

Frans T.M. Nieuwstadt, 1946-2005 (Photo: Nout Steenkamp/FMAX/FOM)

Obituary Prof. Frans T.M. Nieuwstadt

Laboratory for Aero and Hydrodynamics, Leeghwaterstraat 21, 2628 CA Delft, The Netherlands

Frans Nieuwstadt has been a professor of fluid mechanics since 1986. He died under rather tragic circumstances on May 18, 2005. He made several profound contributions to research in turbulent shear flows, first in meteorology and later in engineering.

Frans was born in 1946. After secondary school he studied aerospace engineering at the Technische Hogeschool in Delft (now known as TU-Delft). After his university education he spent two years at the California Institute of Technology, studying computational fluid mechanics. He very much enjoyed this period, especially because of the informal relation between students and professors. At that time the student-professor relation was still very formal in the Netherlands.

After leaving Caltech, he accepted a position at the Royal Dutch Institute for Meteorology (KNMI). Here he worked on atmospheric boundary layers. In 1981 he got his PhD, with Henk Tennekes as PhD adviser, on the behavior of the nocturnal boundary layer. This work initiated his international reputation. Best known is his model of the stable boundary layer that (with a few modifications) has since been regarded as the standard model.

In 1986 he was appointed Professor of fluid mechanics at TU-Delft. Among his predecessors were renowned persons such as J.M. Burgers and J.O. Hinze. Due to various circumstances, the fluid mechanics Chair at Delft had been vacant for more than two years and a whole new group needed to be formed. Frans proved to be a worthy successor and successfully took up this challenge.

During his time at KNMI he had been working on Large Eddy Simulation of the atmospheric boundary layer. He saw the merit of this type of techniques for engineering flows and initiated various projects on the Large Eddy Simulation of pipe and jet flows. He also noticed that this type of work could not be performed without the backup by accurate experimental data. So an extensive experimental program, using Laser Doppler Anemometry and later Particle Image Velocimetry (PIV) was also developed in his laboratory. The combination of the numerical and experimental research turned out to be very successful and formed the backbone of the laboratory. Frans believed strongly in this combination of approaches which forms one of his lasting legacies to us.

He noticed that it became more and more difficult to get funding for pure (fundamental) turbulence research. He developed a program he called 'turbulence plus', i.e., a turbulent flow plus for instance chemical reactions, suspended particles or polymers. This turbulence-plus program resulted in several very successful PhD projects and many publications in the Journal of Fluid Mechanics and Physics of Fluids.

Frans was one of the founders of the JM-Burgerscentre, a national research school for fluid mechanics and related phenomena in the Netherlands. He initiated a number of activities that contributed directly to the excellent collaboration among the various groups in this research school. In this respect, particular mention may be made of the bi-annual meetings of the Dutch turbulence interest group. As a result of his motivating energy, fluid mechanics is a flourishing research-field in the Netherlands, with more than 200 enlisted PhD students. Internationally he was also very active. He saw the value to his laboratory of the new networks that have sprung up in Europe including Euromech, ERCOFTAC, and the European Turbulence Conferences (which he chaired 1990-1996). He also supported the conference of the International Union of Theoretical and Applied Mechanics.

Frans was a marvelous companion to everyone in his laboratory and took great pride in having a family atmosphere, and dealing gently but firmly with the managerial and personal difficulties that arise in any organization. Among the students in Delft he was well known for his inspiring lectures, an honor much appreciated by Frans. The door of Frans his office was always open. If one of the employees of the department, or one of his (former) students had a problem, concerning work as well as personal problems, Frans was always there to solve the problem. Also on a national level he was a key player in many scientific organizations, among others he was the president of the Foundation for Fundamental Research of Matter (FOM) until his untimely death on May 18th, 2005. We cherish this image of Frans as initiator, motivator and personal friend, and will miss him dearly.

Colleagues of the laboratory for Aero and Hydrodynamics, June 2005.

A few characteristic publications of Frans Nieuwstadt

i. Nieuwstadt, F. T. M.; Mason, P. J.; Moeng, C. H.; Schumann, U., 1991, Large-eddy simulation of the convective boundary layer - A comparison of four computer codes. IN: Symposium on Turbulent Shear Flows, 8th, Munich, Federal Republic of Germany, Sept. 9-11, 1991, Proceedings. Vol. 1 (A92-40051 16-34). University Park, PA, Pennsylvania State University, 1991, p. 1-4-1 to 1-4-6.

ii. Eggels, J., Unger, F., Weiss, M., Westerweel, J., Adrian, R., Friedrich, R. & F.T.M. Nieuwstadt, 1994, Fully developed turbulent pipe flow: a comparison between direct numerical simulation and experiment, *J. Fluid Mech.*, **268**, 175-209.

iii. Draad, A.A., & F.T.M. Nieuwstadt, 1998, The Earth's rotation and laminar pipe flow, *J. Fluid Mech.*, **361**, 297-308.

iv. Brethouwer, G., J.C.R. Hunt, & F.T.M. Nieuwstadt, 2003, Micro-structure and Lagrangian statistics of the scalar field with a mean gradient in isotropic turbulence, *J. of Fluid Mech.*, **474**, 193-225.

v. B. Hof, C. W. H. van Doorne, J. Westerweel, F. T. M. Nieuwstadt, H. Faisst, B. Eckhardt, H. Wedin, R. Kerswell, F. Waleffe, 2004, Experimental Observation of Nonlinear Traveling Waves in Turbulent Pipe Flow, *Science*, **305**, Issue 5690, 1594-1598 .

Preface

The sixth ERCOFTAC Workshop on 'Direct and Large-Eddy Simulation' (DLES-6) was held at the University of Poitiers from September 12-14, 2005. Following the tradition of previous workshops in the DLES-series, this edition has reflected the state of the art of numerical simulation of transitional and turbulent flows and provided an active forum for discussion of recent developments in simulation techniques and understanding of flow physics. At a fundamental level this workshop has addressed numerous theoretical and physical aspects of transitional and turbulent flows. At an applied level it has contributed to the solution of problems related to energy production, transportation and the environment.

Since the prediction and analysis of fluid turbulence and transition continues to challenge engineers, mathematicians and physicists, DLES-6 has covered a large range of topics from more technical ones like numerical methods, initial and inflow conditions, the coupling of RANS and LES zones, subgrid and wall modelling to topics with a stronger focus on flow physics such as aero-acoustics, compressible and geophysical flows, flow control, multiphase flow and turbulent combustion, to quote only a few.

In total 141 participants from 16 countries registered for this workshop. The ERCOFTAC support stimulated the organization in a number of essential ways. The specific ERCOFTAC grant allowed easier participation at this workshop for the 42 PhD students. The 33 ERCOFTAC members present in DLES-6 could also benefit from the sponsoring.

The present proceedings contain the written versions of 7 invited lectures and 82 selected and reviewed contributions which are organized in 16 parts entitled *'Turbulent Mixing and Combustion', 'Subgrid Modelling', 'Flows involving Curvature, Rotation and Swirl', 'Free Turbulent Flows', 'Multiphase Flows', 'Wall Models for LES', 'Complex Geometries and Boundary Conditions', 'Flow Control', 'Heat Transfer', 'Aeroacoustics', 'Variable Density Flows', 'Inflow/Initial conditions', 'Separated/Reattached Flows', 'Hybrid RANS-LES Approach', 'Compressible Flows',* and *'Numerical Techniques'.*

The workshop was financially supported by the Association Française de Mécanique, Centre National de la Recherche Scientifique (SPI), Ecole Nationale Supérieure de Mécanique et d'Aérotechnique, European Research Community On Flow, Turbulence and Combustion, J.M. Burgers Centre, Laboratoire d'Etudes Aérodynamiques-UMR6609, Ministère de l'Education Nationale de l'Enseignement Supérieur et de la Recherche, Région Poitou-Charentes (Programme Com'Sciences), Université de Poitiers (Faculté des Sciences), Ville de Poitiers, Communauté d'Agglomération de Poitiers. The organizers of this workshop express their sincere gratitude to these sponsors.

Poitiers,
January 2006

Eric Lamballais
Rainer Friedrich
Bernard J. Geurts
Olivier Métais

Contents

Part XVI Compressible Flows

Part XVII Numerical Techniques and POD